

Open Research Online

The Open University's repository of research publications and other research outputs

An internet of laboratory things

Conference or Workshop Item

How to cite:

Drysdale, Timothy D. and Braithwaite, N. St.J. (2017). An internet of laboratory things. In: 2017 4th Experiment@International Conference (exp.at'17), pp. 236–240.

For guidance on citations see [FAQs](#).

© [not recorded]



<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Version: Accepted Manuscript

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1109/EXPAT.2017.7984362>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

An Internet of Laboratory Things

Timothy D. Drysdale, N. St. J. Braithwaite, and The OpenSTEM Labs team
Faculty of Science Technology Engineering and Mathematics
The Open University
Milton Keynes, MK7 6AA, United Kingdom
tim.drysdale@open.ac.uk, n.s.braithwaite@open.ac.uk

Abstract— By creating “an Internet of Laboratory Things” we have built a blend of real and virtual laboratory spaces that enables students to gain practical skills necessary for their professional science and engineering careers. All our students are distance learners. This provides them by default with the proving ground needed to develop their skills in remotely operating equipment, and collaborating with peers despite not being co-located. Our laboratories accommodate state of the art research grade equipment, as well as large-class sets of off-the-shelf work stations and bespoke teaching apparatus. Distance to the student is no object and the facilities are open all hours. This approach is essential for STEM qualifications requiring development of practical skills, with higher efficiency and greater accessibility than achievable in a solely residential programme.

Keywords— *Remote laboratory, web interface, HTML5, peer-to-peer video, webrtc, websockets, research-grade equipment, large-scale laboratory*

I. INTRODUCTION

The world is now connected to an unprecedented degree. Fibre-optic cable encircles the globe. Data packets and control commands can circumnavigate the world in the same time that it takes a human to react to an event occurring right in front of them. Thus there is now no longer a compelling argument to routinely incur the cost of co-locating humans and equipment. Many companies operate multi-nationally, and find themselves turning to a default approach of “digital first.” Thus, it is no longer possible to assume science, technology, engineering and mathematics (STEM) students will primarily find jobs that involve working with people in the same time-zone, let alone the same building. Facing this future, students need to learn to operate equipment and collaborate at a distance, if they are to be adequately prepared for their careers in science and engineering.

II. CONTEXT

Remote practical work can take a number of forms. For example, posting low-cost equipment to the student [1], providing simulation environments, including immersive virtual reality environments [2], or providing a remote connection to equipment [3]. The increasing use of touch-screen and mobile-phone based interfaces to equipment indicates the growing trend for computers to mediate human interactions with equipment, and laboratory work is no different [4]. Thus remote laboratory work can be considered in some cases, as simply extending the physical distance between the physical interface and the equipment it controls, rather than

a fundamental change in the nature of the interaction. An advantage of the remote interaction is that experiments with hazards such as extreme temperature, extreme pressure, ionising radiation, or noxious chemicals can be more readily arranged than in a conventional setting. Even without obvious hazards, remote experiments can offer either efficient access to limited resources (via asynchronous connections), or extended access (via synchronous connections). Synchronous connections not only facilitate tutor support [5] but also self-led experiential learning [6]. Because even small delays can cause the human brain to expend effort in memorisation [7], latency is undesirable in synchronous remote laboratories. However, broadband connections are increasingly available, and communications provision to institutional facilities can be arranged with sufficient bandwidth to support large class sets of remote experiments, without compromising the bandwidth available to individual students. Large class sets of apparatus address the perceived preference for students to work individually when gathering data remotely [8]. The use of large class sets also aids organisations in providing shared access to remote practical work on a short timescale, due to the flexibility in allocating students to equipment [9]. On the other hand, research grade equipment can be made available in smaller quantities, allowing individuals, as well as small and large groups, to benefit from interaction with equipment that they would not otherwise expect to see until beginning a research degree or moving to industry.

III. CURRENT APPROACH

In our Internet of Laboratory Things, we are tackling the challenge of teaching students to work and collaborate at a distance from the equipment. Our labs are a blend of real and virtual spaces, and they are open all hours. All our students are distance learners, providing a natural training environment for the skills of remotely operating equipment and collaborating with their peers. We support a broad range of curriculum in the domain of STEM subjects. Our approach embraces a range of diverse, and customised examples of remotely operated apparatus. We use the term ‘Internet of Laboratory Things’ to reflect this diversity.

For some topics we focus on using research grade apparatus for which we have designed simplified student-interfaces. Researchers get excited about using research-grade equipment in the education process. They transfer that enthusiasm to the students they are educating. For example, whether teaching students about *pn*-junctions or fruit flies, educators armed with

a scanning electron microscope (SEM) can take a whole class of students on an intimate journey across a real pn-junction or around a biological specimen. An example of one of our SEM experiments and our interface are shown in Fig. 1.

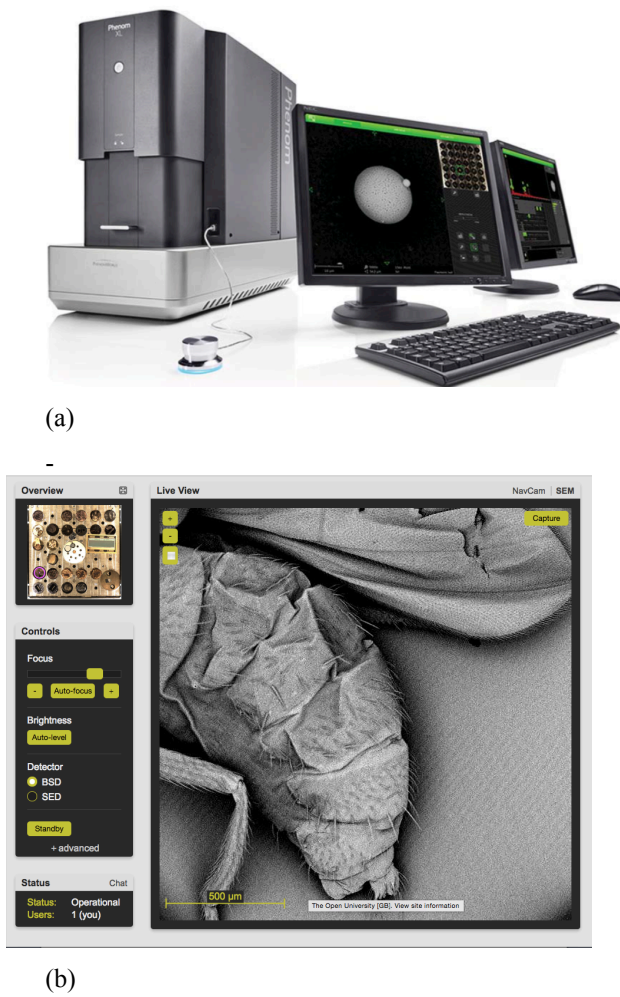


Fig. 1 An example of our use of research grade equipment (Scanning Electron Microscope, SEM) in the education process: (a) photograph of the SEM, (b) screenshot of the web interface as seen/operated by the student.

For other topics, we use Universal Serial Bus (USB)-connected apparatus, with many copies of the same work station running in parallel. Each station hosts apparatus for a lab session and serves one or more students, supporting individual or collaborative learning as appropriate to the exercise. Our laboratory infrastructure brokers the communications between the student and the equipment, then steps out of the way. This allows the peer-to-peer video and control data to flow rapidly, and directly, between the student and the equipment, without being relayed or delayed by a media server. This facilitates low latency required for users to experience real-time control. The connection process is represented schematically in Fig. 2, with the initial phase of brokering in Fig. 2(a) where the student and the equipment communicate with the lab management software, and in Fig. 2(b) the second stage (which lasts for the duration of the

experiment) in which the student and the equipment communicate directly without further intervention from the lab management system.

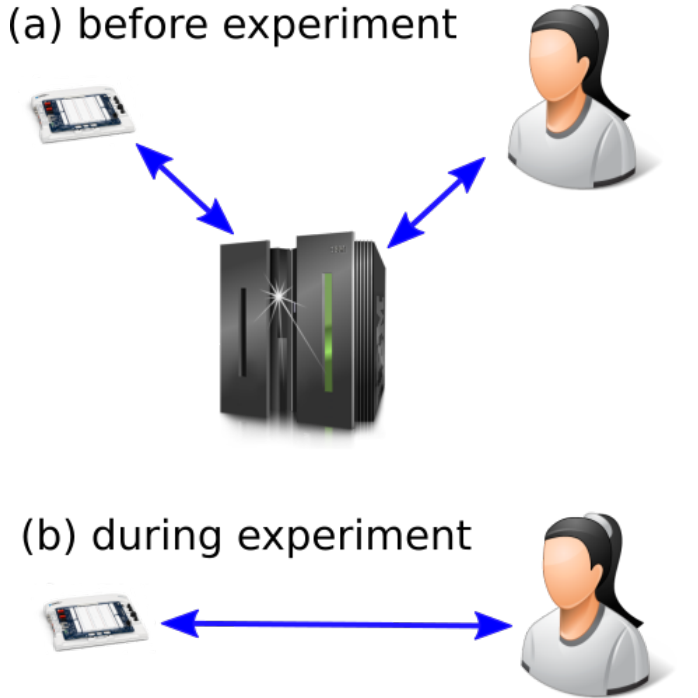


Fig. 2. Our laboratory infrastructure can broker peer-to-peer connections to minimise the latency in video and data connections

The low latency of the peer-to-peer approach facilitates connections from even distant terrestrial locations, so long as sufficient bandwidth is available (a minimum of approximately 1 Mbits^{-1}), and with appropriate firewall settings for WebRTC [10]. Such conditions are typically available for our target students within the UK, but also further afield.

All of these connections have been facilitated by our use of HTML5 web interfaces. This ensures compatibility with a range of browsers and the most common internet-enabled communication devices (PCs, laptops, tablets, and smart phones). We have received connections from the USA, Europe and Asia, with notable examples occurring from Death Valley (below sea level), an intercity express travelling at 200 km h^{-1} , and from airplanes flying at over 30,000 feet, as shown in Fig. 3.

IV. BENEFITS OVER CONVENTIONAL APPROACHES

Remote laboratories offer a number of advantages for distance learners, as well as providing a route to teaching students in face-to-face environments about how to operate in a connected world (with a particular application to joint-degree programmes that cross national borders).



Fig 3. Tweets about successful connections from challenging locations (a) Death Valley, which is below sea level; (b) at cruising altitude in an airliner; and (c) on a high-speed train.

On-campus labs for face-to-face teaching typically are restricted to office hours, and there are strict limits on the nature of experiments that can be conducted when operators are in the vicinity of the apparatus. Home experiment kits for distance learners also are not ideal; Table I lists some of the issues we have encountered. On the other hand, remote laboratories in general, and our Internet of Laboratory Things in particular, have the benefits as listed in Table II. Nevertheless, we note that contemporary approaches continue to include the use of home experiment kits [1], that can be cost effective for subjects such as electronics exploiting the ready availability of components that are volume manufactured for other markets, such as microcontrollers.

TABLE I. DISADVANTAGES OF A HOME EXPERIMENT KIT

Restrictions on what you can send out
Space required to operate it safely
Fault finding service for when it doesn't go right
Cost of return, checking, repair and warehousing

TABLE II. ADVANTAGES OF REMOTE LABORATORIES

Increased cost effectiveness; apparatus can be worn out before it is out of date
Facilitates collaborative peer learning
Safe working with high voltage, radiation, noxious fumes, hazardous liquids, high noise levels, moving parts.
Accessibility improvements for a wide range of impairments

V. CURRICULUM SUPPORT

Our diverse range of equipment targets all areas of STEM education, with a particular focus on remote instruments for physics, chemistry, biosciences, astronomy, electronics,

robotics, environmental sciences and space sciences. A summary of our equipment is listed in Table III.

TABLE III. OUR EQUIPMENT INVENTORY (MAY 2017)

Quantity	Item
2	Scanning electron microscopes (with sample tilt capability)
2	Optical microscopes
6	Analytical-chemistry instruments
1	Flow-chemistry reactor
3	X-Ray scattering and absorption sets
2	High-energy particle tracking cameras
1	5 m radio telescope
2	Optical telescopes (17" and 14")
1	Satellite ground station and a component of payload in orbit
2	Optical telescopes with X-Y stages
1	Enclosed Mars/Lunar landscape and remote-controlled rover
88	Benchtop electronics work-stations (NI ELVIS)
156	Experimental modules for electronics (off the shelf, 4 types)
160	Experimental modules for electronics (bespoke, 4 types)
112	Mobile units (72 myRIOS and 40 myDAQs)
76	Switch matrices
95	PCs
200	Webcams
7	Programmable human-size collaborative robots (Baxter)
1	Studio-lab for live streaming experiments

VI. COLLABORATION

We enable collaboration on our scientific experiments by integrating standard networking. This enables a non-co-located team of students to operate telescopes and analytical instruments together. The controls are shared, and the students can communicate using any additional means that is appropriate or preferable to them, e.g. instant messaging, Skype and Google Hangouts. All students have a control panel, and can use the communications channels to plan and execute the work, each student taking responsibility at various stages.

In engineering, the peer-to-peer video communications also naturally supports collaborative work. For many of our experiments it is possible to control them collaboratively with some students using PCs and other using mobile phones. In this way, the laboratory is not prescriptive about the equipment you should use. This facilitates more natural interactions that accommodate the preferences of the individual users. A further consequence of allowing remote access is that physical impairments become less of a barrier to participation.

VII. LAB MANAGEMENT

We have developed and are continually evolving our software platform that hosts our Internet of Laboratory Things.

We have been required to adapt commercial equipment that was not originally intended for routine, web-based student-use. The transition to the web-based interface does not limit the controls that we can provide to the student. However, we do specifically choose which controls to make available for a given experiment, based on pedagogic need.

Further, the platform is designed to permit maximum flexibility in the choice, and location, of equipment. Because we are using real instruments, the optimum physical location is determined by operational requirements, whether inside fume-hoods or on roof-tops or up mountains or in orbit. Thus our equipment is distributed across our campus and further afield to other locations and nations as required.

We have arranged for secure connectivity through institutional firewalls where it is required to facilitate the low latency digital communications that are essential for real-time control of equipment. For the research grade equipment, secure subnets are available to increase the system robustness. To manage the equipment in these separate locations, our software platform offers instrument and connection status dashboards for staff to monitor the operation of the laboratory.

The platform includes an integrated booking system, and we have successfully extended use of our service to third party institutions for use in their own courses.

VIII. USER EXPERIENCE

The user experience begins with the booking system, where they select the experiment they want to do, and the time they want to do it (as prompted by the virtual learning environment that hosts their coursework). When it is time for the students to conduct their experiment, our platform provides them a web link to an HTML5 interface.

They do not need to download or install any plugins or special software. This approach ensures compatibility with a range of browsers and the most common internet-enabled communication devices (PCs, laptops, tablets, smart phones). The interfaces are developed with accessibility considerations in mind right from the beginning. There are data-management systems to store and distribute high-resolution image files, and video so that the students have a record of their work.

Our interface designs reflect the nature of the practical exercise. Our guiding philosophy is that we must offer authentic interfaces that allow students to gather real data.

For our research-grade equipment, the interfaces allow the same breadth of interactions as the original physical interface, although we present the design using broadly-interpreted Flat 2.0 design guidelines. We do not attempt to represent the equipment in a skeuomorphic fashion, instead letting the real data speak to the genuine nature of the experiment. An example is shown in Fig. 1(b). The interfaces represent all of the necessary features for the exercise.

For our teaching apparatus, such as in electronics, we adopt an approach that mimics the reconfigurable nature of an electronics test bench. In addition to the standard test and measurement equipment such as a power supply, multimeter, function generator and oscilloscope, a student would expect to

see any additional specialist equipment, circuit boards, and test items, as well as reconfigure their locations and settings as you go, as determined by your experimental agenda. Thus we provide a number of windows that can be moved and sized as desired by the student. This allows them to retain their autonomy in working through an experiment, by letting them choose which view they would prefer at any given time. A schematic of the concept is given in Fig. 4.

The interface for each experiment is provisioned with appropriate customised windows. The need for such an approach was evidenced from interviews taken as part of an eye-gaze study. We recruited 20 post-graduate students from our faculty. The test involved a 15 - 45 minute session using a prototype HTML5 interface presented on a Tobii infrared eye tracker system [11]. The eye-gaze system comprised a monitor with integral infra-red transmitters and receivers. The students

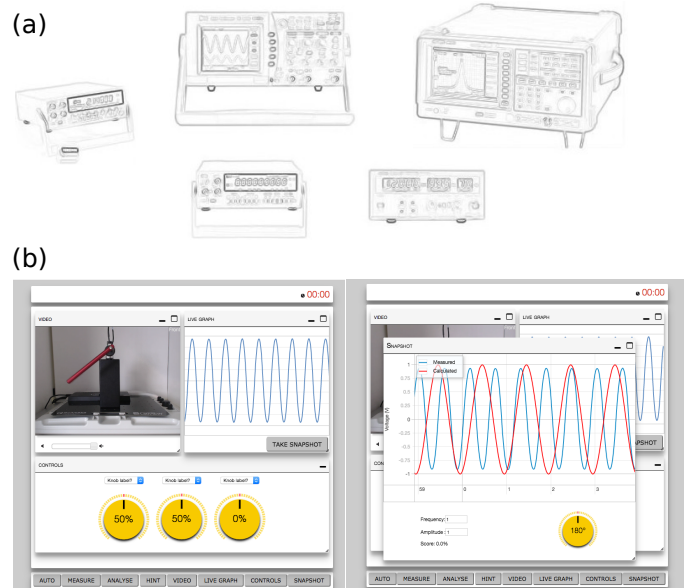


Fig. 4. Reconfigurable interface mimics the reconfigurable nature of an electronics test bench (a) schematic of a test bench, (b) screenshots of the web interface for an electronics activity (recent prototype).

were supervised by a research assistant. An example series of 10-second sequences of eye movements from one of the test subjects is shown in Fig. 5. The sequences indicate the eye moving between one, two or three panes of the six-pane interface at a time.

Open-ended feedback from participants revealed that there was a slim majority consensus view on the optimum fixed placement of the windows to reduce the eye travel required to accomplish the task. On the other hand, allowing the freedom to place them as required would suit a wider range of students, and so the interface was improved to accommodate resizable and movable panes (as already shown in Fig. 4). It also provides the opportunity to present a simpler interface on loading the web page, and introduce additional windows later, such as for analysis.

IX. EVOLUTION

The Open University's engagement with practical work in distance learning began when it was founded as a distance learning institution in 1969. Home experiment kits were sent to students. In the early 2000s, the institution explored remote laboratory work as part of the "part-time education for adults returning to learn" (PEARL) project [3,12], along with Trinity College Dublin and the University of Porto. Equipment included a spectrophotometer, and students could even upload scripts to run the hardware. Meanwhile, a number of courses continued to send ever-advancing home experiment kits to students, such as a micro-controller based sensing unit used in computing courses. Now, our approach has evolved such that remote access to laboratories is favoured over sending home experiment kits, leading to the expanded provision described in this paper. We continue to embed accessibility into our activities so as to maintain our institutional values of being open to people, places, methods and ideas.

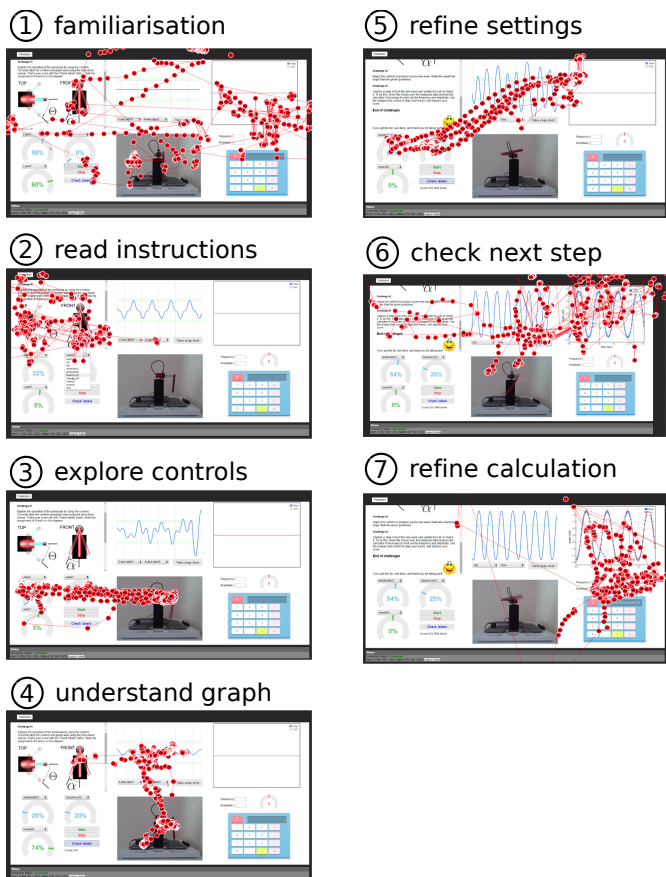


Fig. 5. Example 10-second sequences of eye movement obtained during gaze tracking tests, using an early prototype of the HTML5 interface.

X. CONCLUSION

We have developed a large scale remote laboratory facility that supports our university curriculum across a broad range of science, technology, engineering and mathematics subjects. We call it our Internet of laboratory Things, reflecting the eclectic nature of general purpose STEM Labs. We are using our online

labs in our curriculum. Our Internet of Laboratory Things is also an observatory for human-computer interactions and we will continue to gather user interaction data from which to improve usability. We have an integrated software platform to allow students to book sessions, and staff to monitor equipment. Our provision includes research grade equipment, multiple copies of teaching apparatus, and external facilities such as microscopes. Our interfaces are provided in HTML5 to ensure that students can access our laboratories on the broadest range of computing devices, from PCs to mobile phones. This also allows us to accommodate pedagogic aspects such as reflecting the reconfigurable nature of an experiment conducted with separate test equipment items, and to enable greater accessibility to practical work than compared to conventional laboratories. Students can book sessions through the day or night, rather than being restricted to conventional office hours. The low latency of our approach makes it suitable for use from any terrestrial location with a high-speed broadband connection and appropriately permissive firewall settings.

REFERENCES

- [1] D. A. H. Samuelsen and O. H. Graven "An affordable pocket lab for a module in analogue electronics", in 2016 International Conference on Interactive Mobile Communication, Technologies and Learning (IMCL), San Diego, CA, USA, 2016 IEEE, pp.88-92
- [2] Fayolle, J., Gravier, C., Yankelovich, N., and Kim, E., "Remote lab in virtual world for remote control of industrial processes," 2011 IEEE International Conference on Multimedia and Expo, Barcelona, 2011, pp. 1-4.
- [3] Colwell C., Scanlon E., and Cooper M. (2002). Using remote laboratories to extend access to science and engineering. *Computers & Education*, 38, 65–76.
- [4] Ma, J., Nickerson, and Nickerson, J. V., "Hands-On, Simulated, and Remote Laboratories: A Comparative Literature Review," *ACM Computing Surveys*, Vol. 38, No. 3, Article 7, September 2006.
- [5] Böhne, A., Faltin, N., and Wagner, B., "Synchronous Tele-tutorial Support in a Remote Laboratory for Process Control," *International Conference on Engineering Education*, July 21–25, 2003, Valencia, Spain.
- [6] Zunzarren, G. M., "The error as a problem or as teaching strategy," *Procedia - Social and Behavioral Sciences* Vol. 46, 3209 – 3214, 1877-0428, 2012
- [7] Kahneman, D. (2011). *Thinking, Fast and Slow*. New York, NY US: Farrar, Straus and Giroux
- [8] Corter, J.E., Esche, S.K., Chassapis, C., Ma, J., and Nickerson, J.V., "Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories," *Computers & Education*, Vol. 57, Iss. 3, November 2011, Pages 2054–2067
- [9] Lowe, D., Dang, B., Daniel, K., Murray, S., Lindsay, E., "On the viability of supporting institutional sharing of remote laboratory facilities," *European Journal Of Engineering Education* Vol. 40 , Iss. 6, 2015
- [10] WebRTC 1.0: Real-time Communication Between Browsers, W3C Editor's Draft 08 May 2017, <https://w3c.github.io/webrtc-pc/>
- [11] T. D. Drysdale, M. Brodeur, N. St. J. Braithwaite, "Eye-gaze tracking of remote laboratory users to quantify reliance on video," 6th International Symposium for Engineering Education Interdisciplinary Engineering, Sheffield, UK, 14 - 15 July 2016
- [12] M. Cooper, A. Donnelly, J. M. M. Ferreira, "Remote controlled experiments for teaching over the Internet: A comparison of approaches developed in the PEARL project," *Proceedings of the 19th annual conference of the Australian Society of Computers In Learning In Tertiary Education*, 2002.